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News on ^{12}C from β-decay studies

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We discuss the importance of the spectroscopic properties of the resonances of ^{12}C just above the 3α-threshold, and review the existing experimental information of this region with emphasis on 0^+ and 2^+ states. A new experimental approach for studying the β-decays of ^{12}B and ^{12}N is presented based on techniques developed in the context of Radioactive beam (rare isotope) physics. Finally preliminary results from an ongoing analysis of two recent experiments are given.

1. Introduction

^{12}C is the fourth most abundant nuclear species observed in the universe, but in the energy region just above the 3α-threshold broad overlapping resonances make spectroscopy very challenging, and so significant uncertainties still remain on the low energy nuclear spectroscopic properties of this isotope.

The spectroscopic properties of this region are closely linked to the understanding of the cluster structure of ^{12}C. Different configurations of the three α-particles predict different rotational bands, thus experimental knowledge of the position of specific states can be used to infer the underlying structure of ^{12}C. Recent examples of these arguments are given in Refs. [1–3], where it is pointed out that the spectroscopic properties of the 0_3^+, 2_2^+ and 2_1^- resonances should be reevaluated experimentally to clarify the situation. Recently there are also a number of benchmark calculations on the 3α system for which more

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precise data would be highly beneficial [4–8].

The α-cluster structure of ^{12}C and other 4N nuclei has recently been reinterpreted as an α-particle condensation in analogy with Bose-Einstein condensation of dilute gases, see the contributions of P. Schuck, A. Tohsaki, H. Matsumura, Y. Funaki and T. Yamada to these proceedings [9].

In addition there is much progress in performing large scale no-core shell model calculations for p-shell nuclei. The most recent calculation for ^{12}C includes a realistic three-body force and up to $4\hbar\Omega$ excitations [10], but this model space is still too limited to reproduce the positions of states with cluster structure. In contrast, the anti-symmetrised Molecular Dynamics [2,11] and Fermionic Molecular Dynamics [12] approaches succeed in reproducing both many-body and cluster type features of ^{12}C. Finally, "exact" Green-function and variational Monte-Carlo calculations performed by the Argonne-Urbana groups are now becoming possible for the A=12 system [13]. It will be interesting to follow how the many-body and cluster features appear in these calculations, although the fact that the most interesting states are situated in the 3α-continuum might present a significant difficulty there.

It is well known that the 7.654 MeV state in ^{12}C plays an important role in astrophysics by enhancing the reaction rate of the triple-α process in red giant stars [14]. The European compilation of astrophysical reaction rates NACRE [15] assumes in addition a 2^+ state at 9.2 MeV, which at temperatures above 10^9 K (as e.g. in x-ray bursters) significantly speeds up the triple-α process. The possible existence of this state is deduced from cluster type calculations [16] with no experimental corroboration. Additionally, if a broad 0^+ state is situated just above the 7.654 MeV state, as seems to be case, there will be an interference between the two states which depends on the poorly known width and position of that state. This could also affect the reaction rate of the triple-α process in a wider temperature region.

The preceding discussion serves to underline that despite numerous studies over many years there is a strong an ongoing interest in the properties of ^{12}C. In the following section we shortly review the existing experimental knowledge with emphasis on the 0_3^+ and 2_2^+ states. In section 3 we describe a new approach for studying ^{12}C and give our preliminary results in section 4. Finally we give an outlook.

2. Previous experimental information

In the latest ^{12}C review from 1990 [17] there are no unambiguously identified 0^+ or 2^+ T=0 states above the 0^+ state at 7.654 MeV. There is a state at 10.3 MeV tentatively assigned as 0^+, and two tentatively assigned 2^+ states at 11.16 MeV and 15.44 MeV. The 10.3 MeV state was first observed in the β-decays of ^{12}B and ^{12}N [18–20], and has since been observed tentatively in $^{13}C(p,d)^{12}C$ [21], and more clearly in inelastic hadron scattering $^{12}C(x,x)^{12}C$, with x=p, ^3He, α and ^6Li [22–24]. The 11.16 MeV state was observed in $^{11}B(^3He,d)^{12}C$ [26], and recently in $^{12}C(\alpha,\alpha)^{12}C$ [27] (but not previously in any other inelastic hadron scattering). The 15.44 MeV state is observed in inelastic hadron scattering, and in electron scattering [25]. Finally, another very recent $^{12}C(\alpha,\alpha)^{12}C$ experiment report on a previously unobserved 2^+ state at 9-10 MeV and with width $\simeq$0.5 MeV [28] (this state is also not seen in any other inelastic hadron scattering).

To summarise this situation is challenging. That different probes see different states can in principle be correct, but when the same probe sees different states in different experiments (as for $^{12}C(\alpha,\alpha)^{12}C$ [23,27,28]), there is clearly a problem. The main problem with the inelastic hadron scattering, and also transfer reaction approaches, is that it is hard to see broad states under the background of the narrower $1,2,3^-$, and $1,4^+$ states situated in the same energy region. In contrast nearly all the mentioned probes identify the narrow resonances in ^{12}C, e.g. the 7.654 MeV 0^+ and 12.71 MeV 1^+ states.

In the β-decay approach the selection rules of β-decay serve to single out the $0,1,2^+$ states. It is puzzling why the previous studies only observe the broad 10.3 MeV state, and none of the candidates for 2^+ states. In an unpublished work on the ^{12}N decay, there are indeed indications for the presence of a state at higher energy [29].

Before closing this discussion a deficiency in most of the previous experimental work should be mentioned. When states of identical spin-parity overlap they interfere such that the total intensity differs from the simple sum of two states. The peak shapes will therefore deviate from Gaussians and the extraction of level parameters becomes non-trivial. It was pointed out already in the early 60s that the 0^+ state at 7.654 MeV due to its position just above the 3α-threshold will have a tail (so called 'Ghost') extending to higher energies [30] (see alse the excellent discussion in [19]). Any other 0^+ state situated in the 7-11 MeV region will interfere with this tail. The same effect will obviously be present for possible overlapping 2^+ states.

3. New experimental approach

The previous studies of the ^{12}B and ^{12}N decays all employed the reactions $^{11}B(d,p)^{12}B$ and $^{10}B(^3He,n)^{12}N$ to produce the activity, which was measured directly from the target. Thus a common problem was the energy loss of the delayed α-particles in the target. Corrections for this are based on assumptions on the source position and are therefore model dependent. Since the conclusions on branching ratios, break-up mechanisms and the determination of energy and width of participating resonances are based on a detailed analysis of the spectra of the delayed α-particles (which are already complicated by the kinematics of the three-body breakup), this problem is a significant limitation.

Recent years have seen a rapid improvement in techniques for handling radioactive beams in the push for producing and studying rare nuclei far away from the valley of β-stability. In the Isotope Separation On-line (ISOL) approach short lived isotopes are quickly removed from the target area, where they are produced in a nuclear reaction, then mass separated, and implanted in a thin host. The technique can be applied to species with half-lives as short as $\simeq$ms and is therefore ideally suited for new improved experiments on the ^{12}N and ^{12}B decays (half-lives 11.0 ms and 20.20 ms respectively [17]).

Also the use of Double Sided Strip detectors (DSSD) now allows for efficient detection in coincidence of all emitted particles in the breakup process. One potential problem with many DSSDs is a rather thick dead layer ($\simeq$600 nm), which induces substantial energy loss when low energy particles are detected. We have recently demonstrated how this and other energy loss effects can be corrected for event-by-event when using DSSDs at ISOL facilities [32]. In collaboration with *Micron Semiconductor Ltd* [33] we have developed a new DSSD design with much reduced dead layer to further reduce this problem [34].

4. Results

Using the approach just described we have studied the ^{12}N decay at the IGISOL beam line of the Jyväskylä accelerator laboratory in Finland in 2001, and the ^{12}B decay at the ISOLDE facility at CERN in 2002. The preliminary results are presented in the following.

In both experiments ISOL beams of 40 KeV energy were transferred to the detection system where they were stopped in a thin carbon collection foil. The detection system, described in detail in [31], consisted of two DSSDs placed on either side of the collection foil. In the ^{12}N experiment standard DSSDs were used, whereas in the ^{12}B experiment we used the new design for the first time. With both position and energy information for each detected particle, breakup events can be fully reconstructed when two of the three α-particles are detected.

Fig. 1 gives an overview of the data obtained in the two experiments (top ^{12}N, bottom ^{12}B). The left part shows a contour plot with the reconstructed excitation energy in ^{12}C against each of the three individual energies, hence each break-up event is represented by three dots on the same horisontal line; the right part of the figure shows the projection onto the excitation energy axis. With dark shading are shown events with three detected α-particles, and with light shading events with two detected α-particles. By comparing the ^{12}N and ^{12}B data sets it is clear that the use of the new detector design permits detection of lower energy particles.

In the projections the 10.3 MeV and 12.71 MeV states are readily identified. The scatter plot provides an overview of the properties of the decay and subsequent breakup: the diagonal line represents the sequential break-up via the narrow ground state of ^{8}Be, which is characterized by the presence of one high energy and two low energy α-particles in the event. Note that this diagonal extends well beyond the 10.3 MeV state, giving unambiguous evidence for a state at higher energy. The break-up pattern of the 12.71 MeV state is clearly different from that of the 10.3 MeV state with the α-energies distributed in three separated regions.

The breakup mechanism of the 12.71 MeV state is an old problem in nuclear physics, which relates closely to the modern discussion of the mechanism of two-proton radioactivity as discussed by M. Pfützner in these proceedings [35]. A detailed analysis and discussion of this based on the data from the ^{12}N experiment is published in [36]. The feeding of the 12.71 MeV state in the ^{12}B decay is observed here for the first time.

The events in Fig. 1 that proceed to the 3α final state via the ^{8}Be ground state must originate from natural parity states (0^+ or 2^+). To be able to compare our two data sets with each other and with previous measurements we correct the excitation energy spectra obtained from gating on the diagonals in Fig. 1 by the energy dependent detection efficiencies (obtained from Monte-Carlo simulations separately for the two experiments) and by the β-particle phase space factors. This is shown as the histograms in Fig. 2. Apart from the lower detection thresholds in the ^{12}B experiment, and the difference in Q_β values, which explains that the ^{12}N spectrum extends to higher energies, the two histograms are remarkably similar. The points in Fig. 2 are estimated averages of the ^{12}B and ^{12}N points of the previously best measurement (from Fig. 6 of Ref. [20]). There is remarkably good agreement up to 3.5 MeV, which is a sign of the high quality of the previous work performed already in 1966. The full curve in Fig. 2 is a fit to the new data using the formalism derived in [37] which can describe interference between states of same

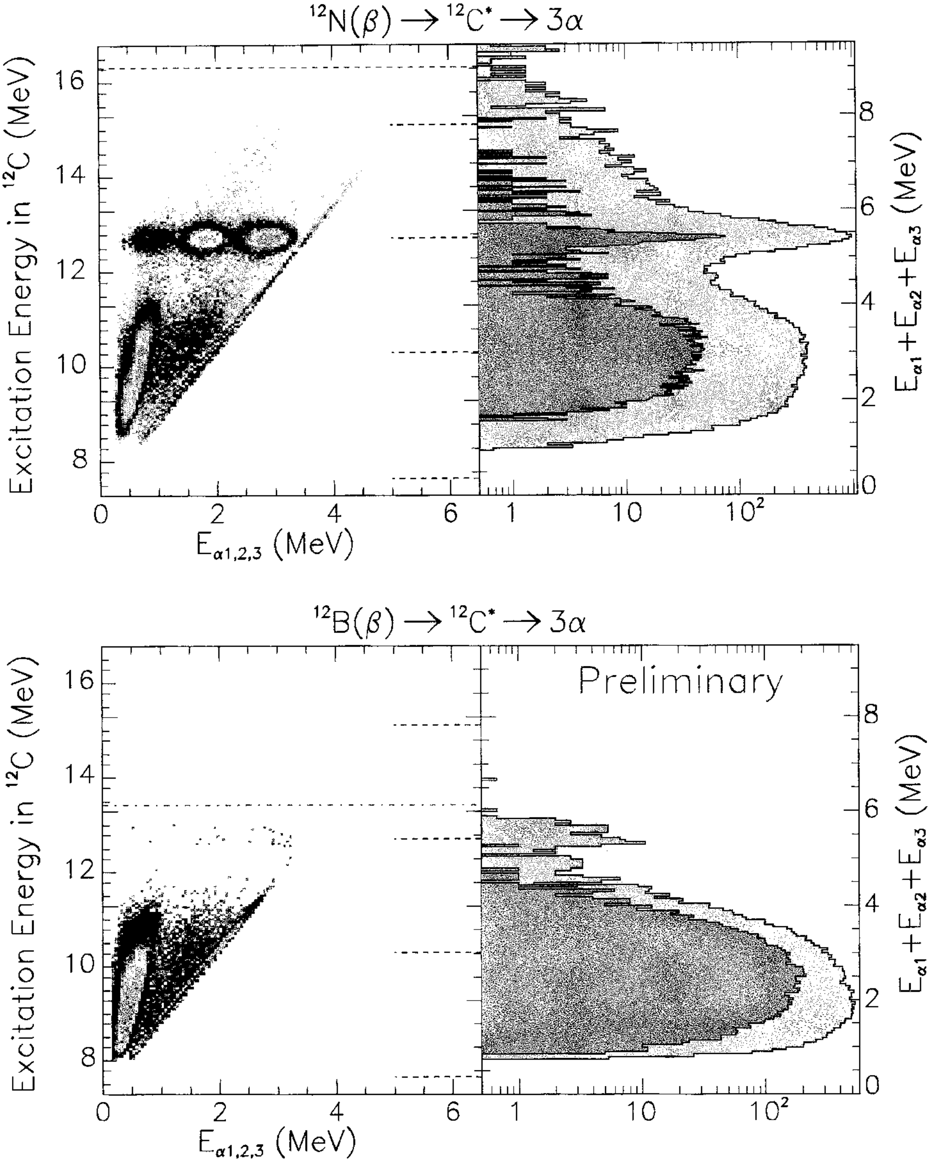

Figure 1. Complete kinematics data for the breakup of unbound states in ^{12}C fed in the β-decays of ^{12}N (top) and ^{12}B (bottom). In each plot the left part shows reconstructed excitation energy in ^{12}C against the energy of the individual α-particle energies. The right part shows the projection on the sum-energy axis. Dark shading is for triple-coincidence events and light shading double-coincidence events. The dashed lines indicate the positions of Q_β thresholds and previously assigned states at 7.654 MeV (0^+), 10.3 MeV ($0,2^+$), 12.71 MeV (1^+) and 15.11 MeV (1^+).

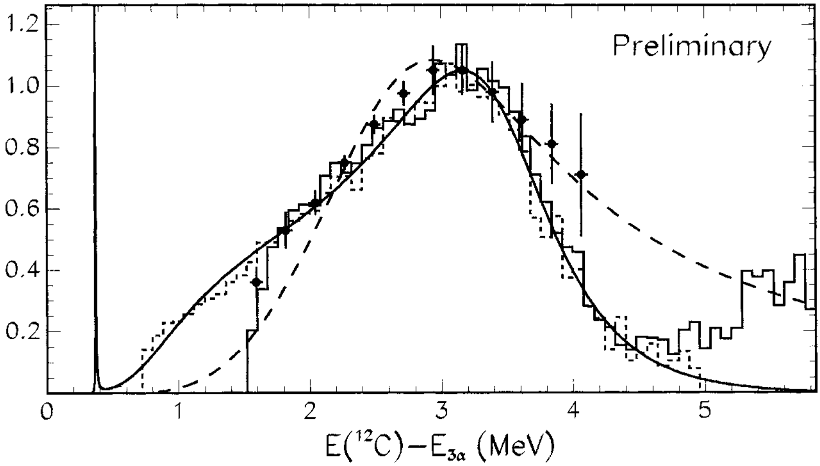

Figure 2. The histograms show the 0^+ and 2^+ states in ^{12}C fed in β-decays, see the text for details. The full histogram is from the ^{12}N data and the dashed histogram from the ^{12}B data. The points show the best previous measurement from Ref. [20]. The full curve is a fit to the new data, and the dashed curve is the fit from [20].

spin-parity as discussed earlier. The fit explains well our data up to an energy of 4.5 MeV, where a higher energy state starts to contribute in the ^{12}N spectrum. The dashed curve is a reproduction of the fit of [20] to their data. It is seen to be a consistent fit to the old data, but it clearly fails to reproduce the new data. Note, the literature parameters of this state are from this fit [17]. The fact that the data can only be well reproduced when the interference effect is included is strong evidence for a 0^+ assignment for this state. The energy of the state is 11.3(2) MeV and the width 2.4(2) MeV (as defined in [37]). The data on the diagonal above 4 MeV in sum energy cannot originate from the 0^+ state and must come from a separate state in ^{12}C (as mentioned earlier, the presence of such a state was hinted at in [29]). In a preliminary analysis it is well fitted as a 2^+ state at $\simeq$ 14 MeV with width $\simeq$ 1 MeV.

5. Outlook

The experiments reported on here leave some questions unanswered. The properties of the high energy state seen in the ^{12}N decay must be further studied. Also, Fig. 2 gives clear evidence for previously unobserved decays via the $^{8}Be(2^+)$ state from the 8-12 MeV region in ^{12}C. Are these decays from the same state as seen in the $^{8}Be(0^+)$ channel? To answer these questions both the ^{12}N and ^{12}B decays will be studied again at the IGISOL beam line of the Jyväskylä accelerator laboratory in Finland in early 2004 using a detector setup covering larger solid angle. As seen in Fig. 2 the α-particles from the 7.654 MeV state are not seen in the present data. A measurement of this region could be feasible by implanting ^{12}N and ^{12}B directly in a detector and in that way directly measure the sum-energy of the three α-particles, as was previously achieved in [38]. Plans for such measurements are in progress.

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